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Standard Test Methods for D-C Resistance or Conductance of Insulating Materials[1]

This standard is issued under the fixed designation D 257; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

These test methods have been approved for use by agencies of the Department of Defense to replace Method 4041 of Federal Standard 406. Consult the DoD Index of Specifications and Standards for the specific year of issue which has been adopted by the Department of Defense.

1. Scope

1.1 These test methods cover direct-current procedures for the determination of d-c insulation resistance, volume resistance, volume resistivity, surface resistance, and surface resistivity of electrical insulating materials, or the corresponding conductances and conductivities.

1.2 The test methods and procedures appear in the following sections:

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1.3 *This standard does not purport to address all of the safety problems associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.* For a specific hazard statement, see Note 1.

2. Referenced Documents

2.1 *ASTM Standards:*

D 374 Test Methods for Thickness of Solid Electrical Insulation[2]

D 618 Methods of Conditioning Plastics and Electrical Insulating Materials for Testing[2]

D 1169 Test Method for Specific Resistance (Resistivity) of Electrical Insulating Liquids[3]

E 104 Practice for Maintaining Constant Relative Humidity by Means of Aqueous Solutions[4]

3. Terminology

3.1 *Descriptions of Terms Specific to This Standard:*

3.1.1 *insulation resistance,* R_i—the insulation resistance between two electrodes that are in contact with, or embedded in, a specimen, is the ratio of the direct voltage applied to the electrodes to the total current between them. It is dependent upon both the volume and surface resistances of the specimen.

3.1.2 *surface resistance,* R_s—the surface resistance between two electrodes that are on the surface of a specimen is the ratio of the direct voltage applied to the electrodes to that portion of the current between them which is primarily in a thin layer of moisture or other semiconducting material that may be deposited on the surface.

3.1.3 *surface resistivity,* ρ_s—the surface resistivity of a material is the ratio of the potential gradient parallel to the current along its surface to the current per unit width of the surface.

DISCUSSION—Surface resistivity of a material is numerically equal to the surface resistance between two electrodes forming opposite sides of a square. The size of the square is immaterial.

3.1.4 *volume resistance,* R_v—the volume resistance between two electrodes that are in contact with, or embedded in, a specimen, is the ratio of the direct voltage applied to the electrodes to that portion of the current between them that is distributed through the volume of the specimen.

3.1.5 *volume resistivity,* ρ_v—the volume resistivity of a material is the ratio of the potential gradient parallel to the current in the material to the current density.

DISCUSSION—In the metric system, volume resistivity of an electrical insulating material in ohm-cm is numerically equal to the volume resistance in ohms between opposite faces of a 1-cm cube of the material. (Volume resistivity in $\Omega \cdot m$ has a value of 1/100 of the value in $\Omega \cdot cm$.)

4. Summary of Test Methods

4.1 The resistance or conductance of a material specimen or of a capacitor is determined from a measurement of current or of voltage drop under specified conditions. By using the appropriate electrode systems, surface and volume resistance or conductance may be measured separately. The resistivity or conductivity can then be calculated when the required specimen and electrode dimensions are known.

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[1] These test methods are under the jurisdiction of ASTM Committee D-9 on Electrical and Electronic Insulating Materials and are the direct responsibility of Subcommittee D09.12 on Electrical Tests.

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[2] *Annual Book of ASTM Standards*, Vols 08.01 and 10.01.

[3] *Annual Book of ASTM Standards*, Vol 10.03.

[4] *Annual Book of ASTM Standards*, Vol 11.03.

5. Significance and Use

5.1 Insulating materials are used to isolate components of an electrical system from each other and from ground, as well as to provide mechanical support for the components. For this purpose, it is generally desirable to have the insulation resistance as high as possible, consistent with acceptable mechanical, chemical, and heat-resisting properties. Since insulation resistance or conductance combines both volume and surface resistance or conductance, its measured value is most useful when the test specimen and electrodes have the same form as is required in actual use. Surface resistance or conductance changes rapidly with humidity, while volume resistance or conductance changes slowly although the final change may eventually be greater.

5.2 Resistivity or conductivity may be used to predict, indirectly, the low-frequency dielectric breakdown and dissipation factor properties of some materials. Resistivity or conductivity is often used as an indirect measure of moisture content, degree of cure, mechanical continuity, and deterioration of various types. The usefulness of these indirect measurements is dependent on the degree of correlation established by supporting theoretical or experimental investigations. A decrease of surface resistance may result either in an increase of the dielectric breakdown voltage because the electric field intensity is reduced, or a decrease of the dielectric breakdown voltage because the area under stress is increased.

5.3 All the dielectric resistances or conductances depend on the length of time of electrification and on the value of applied voltage (in addition to the usual environmental variables). These must be known to make the measured value of resistance or conductance meaningful.

5.4 Volume resistivity or conductivity can be used as an aid in designing an insulator for a specific application. The change of resistivity or conductivity with temperature and humidity may be great **(1, 2, 3, 4)**,[5] and must be known when designing for operating conditions. Volume resistivity or conductivity determinations are often used in checking the uniformity of an insulating material, either with regard to processing or to detect conductive impurities that affect the quality of the material and that may not be readily detectable by other methods.

5.5 Volume resistivities above 10^{21} Ω·cm (10^{19} Ω·m), obtained on specimens under usual laboratory conditions, are of doubtful validity, considering the limitations of commonly used measuring equipment.

5.6 Surface resistance or conductance cannot be measured accurately, only approximated, because some degree of volume resistance or conductance is always involved in the measurement. The measured value is also affected by the surface contamination. Surface contamination, and its rate of accumulation, is affected by many factors including electrostatic charging and interfacial tension. These, in turn, may affect the surface resistivity. Surface resistivity or conductivity can be considered to be related to material properties when contamination is involved but is not a material property in the usual sense.

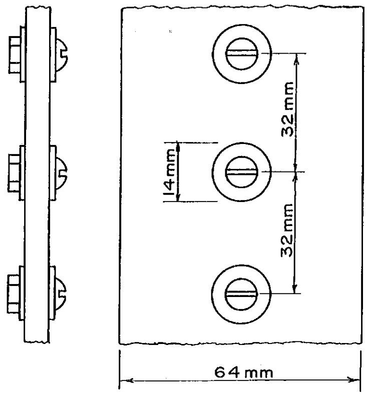

FIG. 1 Binding-Post Electrodes for Flat, Solid Specimens

6. Electrode Systems

6.1 The electrodes for insulating materials should be of a material that is readily applied, allows intimate contact with the specimen surface, and introduces no appreciable error because of electrode resistance or contamination of the specimen **(5)**. The electrode material should be corrosion-resistant under the conditions of test. For tests of fabricated specimens such as feed-through bushings, cables, etc., the electrodes employed are a part of the specimen or its mounting. Measurements of insulation resistance or conductance, then, include the contaminating effects of electrode or mounting materials and are generally related to the performance of the specimen in actual use.

6.1.1 *Binding-Post and Taper-Pin Electrodes,* Figs. 1 and 2, provide a means of applying voltage to rigid insulating materials to permit an evaluation of their resistive or conductive properties. These electrodes simulate to some degree the actual conditions of use, such as binding posts on instrument panels and terminal strips. In the case of laminated insulating materials having high-resin-content surfaces, somewhat lower insulation resistance values may be obtained with taper-pin than with binding posts, due to more intimate contact with the body of the insulating material. Resistance or conductance values obtained are highly influenced by the individual contact between each pin and the dielectric material, the surface roughness of the pins, and the smoothness of the hole in the dielectric material. Reproducibility of results on different specimens is difficult to obtain.

6.1.2 *Metal Bars* in the arrangement of Fig. 3 were primarily devised to evaluate the insulation resistance or conductance of flexible tapes and thin, solid specimens as a fairly simple and convenient means of electrical quality control. This arrangement is somewhat more satisfactory for obtaining approximate values of surface resistance or conductance when the width of the insulating material is much greater than its thickness.

6.1.3 *Silver Paint,* Figs. 4, 5, and 6, is available commercially with a high conductivity, either air-drying or low-temperature-baking varieties, which are sufficiently porous

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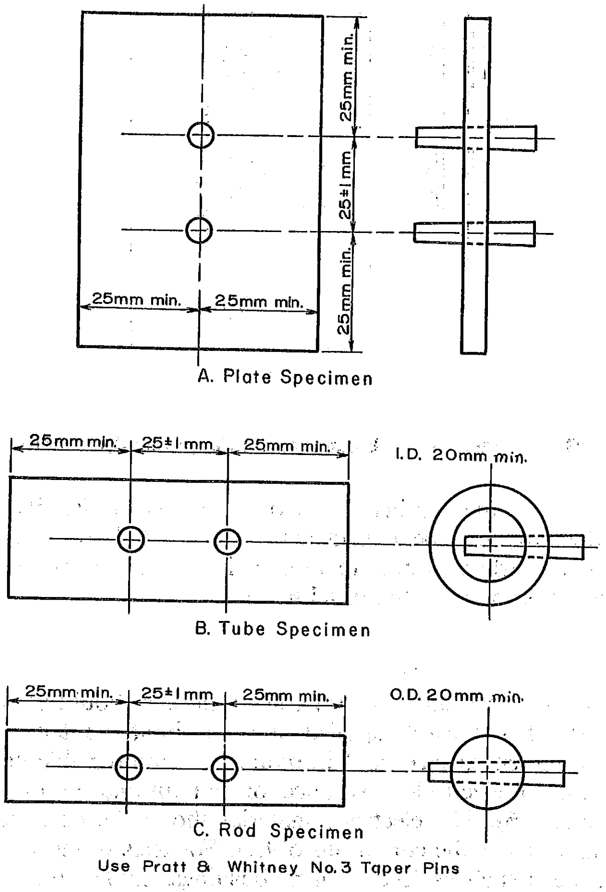
[5] The boldface numbers in parentheses refer to the list of references appended to these test methods.



A. Plate Specimen

B. Tube Specimen

C. Rod Specimen

Use Pratt & Whitney No. 3 Taper Pins

FIG. 2 Taper-Pin Electrodes

to permit diffusion of moisture through them and thereby allow the test specimen to be conditioned after the application of the electrodes. This is a particularly useful feature in studying resistance-humidity effects, as well as change with temperature. However, before conductive paint is used as an electrode material, it should be established that the solvent in the paint does not attack the material so as to change its electrical properties. Reasonably smooth edges of guard electrodes may be obtained with a fine-bristle brush. However, for circular electrodes, sharper edges can be obtained by the use of a ruling compass and silver paint for drawing the outline circles of the electrodes and filling in the enclosed areas by brush. A narrow strip of masking tape may be used, provided the pressure-sensitive adhesive used does not contaminate the surface of the specimen. Clamp-on masks also may be used if the electrode paint is sprayed on.

6.1.4 *Sprayed Metal*, Figs. 4, 5, and 6, may be used if satisfactory adhesion to the test specimen can be obtained. Thin sprayed electrodes may have certain advantages in that they are ready for use as soon as applied. They may be sufficiently porous to allow the specimen to be conditioned, but this should be verified. Narrow strips of masking tape or clamp-on masks must be used to produce a gap between the guarded and the guard electrodes. The tape shall be such as not to contaminate the gap surface.

6.1.5 *Evaporated Metal* may be used under the same conditions given in 6.1.4.

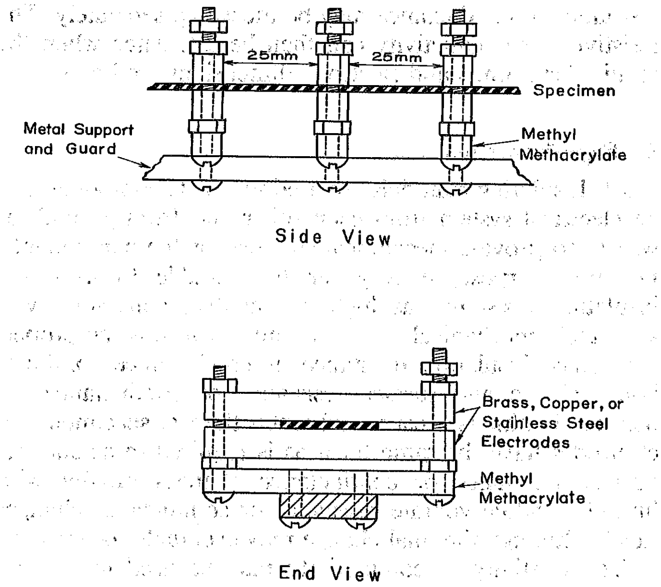
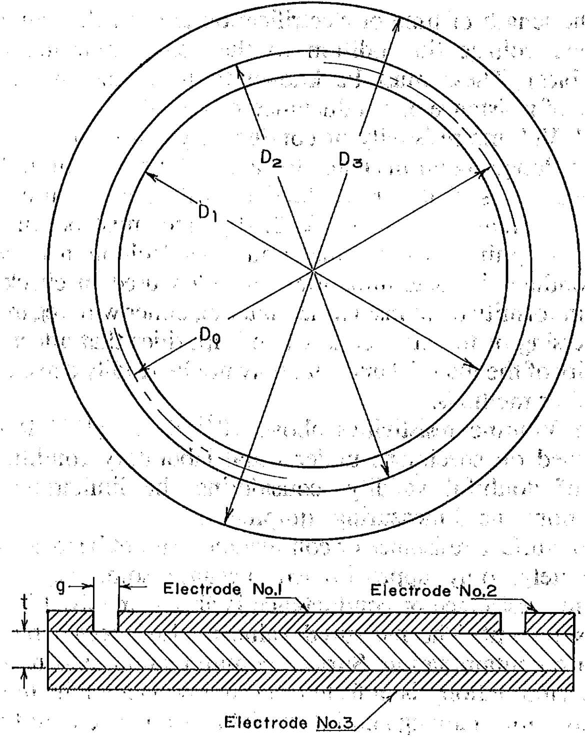


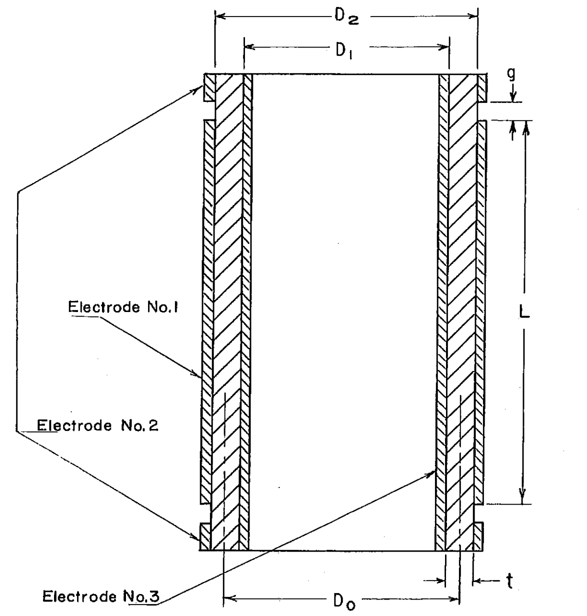
FIG. 3 Strip Electrodes for Tapes and Flat, Solid Specimens

6.1.6 *Metal Foil*, Fig. 4, may be applied to specimen surfaces as electrodes. The usual thickness of metal foil used for resistance or conductance studies of dielectrics ranges from 6 to 80 µm. Lead or tin foil is in most common use, and is usually attached to the test specimen by a minimum quantity of petrolatum, silicone grease, oil, or other suitable material, as an adhesive. Such electrodes shall be applied under a smoothing pressure sufficient to eliminate all wrinkles, and to work excess adhesive toward the edge of the foil



Volume Resistivity g ≧ 2*t* Surface Resistivity

FIG. 4 Flat Specimen for Measuring Volume and Surface Resistances or Conductances



$D_0 = (D_1 + D_2)/2$ $L > 4t$ $g \leqq 2t$ Volume Resistivity $g \geqq 2t$ Surface Resistivity

FIG. 5 Tubular Specimen for Measuring Volume and Surface Resistances or Conductances

where it can be wiped off with a cleansing tissue. One very effective method is to use a hard narrow roller (10 to 15 mm wide), and to roll outward on the surface until no visible imprint can be made on the foil with the roller. This technique can be used satisfactorily only on specimens that have very flat surfaces. With care, the adhesive film can be reduced to 2.5 µm. As this film is in series with the specimen, it will always cause the measured resistance to be too high. This error may become excessive for the lower-resistivity specimens of thickness less than 250 µm. Also the hard roller can force sharp particles into or through thin films (50 µm). Foil electrodes are not porous and will not allow the test specimen to condition after the electrodes have been applied. The adhesive may lose its effectiveness at elevated temperatures necessitating the use of flat metal back-up plates under pressure. It is possible, with the aid of a suitable cutting device, to cut a proper width strip from one electrode to form a guarded and guard electrode. Such a three-terminal specimen normally cannot be used for surface resistance or conductance measurements because of the grease remaining on the gap surface. It may be very difficult to clean the entire gap surface without disturbing the adjacent edges of the electrode.

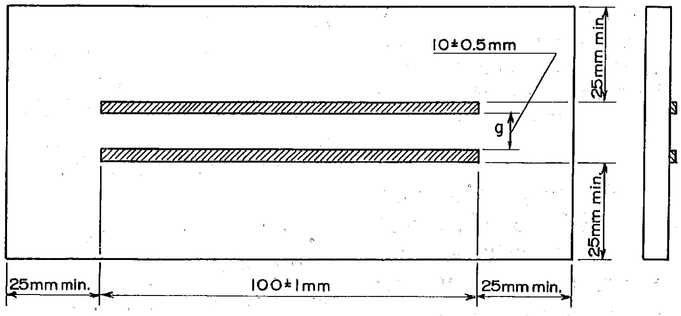
6.1.7 *Colloidal Graphite,* Fig. 4, dispersed in water or other suitable vehicle, may be brushed on nonporous, sheet insulating materials to form an air-drying electrode. Masking tapes or clamp-on masks may be used (6.1.4). This electrode material is recommended only if all of the following conditions are met:

6.1.7.1 The material to be tested must accept a graphite coating that will not flake before testing,

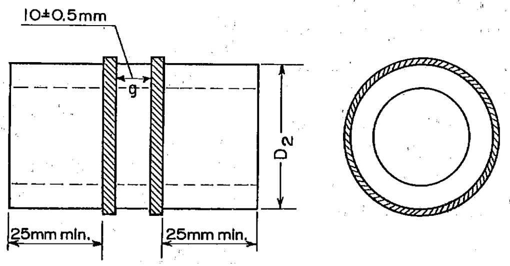
6.1.7.2 The material being tested must not absorb water readily, and

6.1.7.3 Conditioning must be in a dry atmosphere (Procedure B, Methods D 618), and measurements made in this same atmosphere.

6.1.8 Mercury or other liquid metal electrodes give satisfactory results. Mercury is not recommended for continuous use or at elevated temperatures due to toxic effects. (**Caution**—see Note 1.) The metal forming the upper electrodes should be confined by stainless steel rings, each of which should have its lower rim reduced to a sharp edge by beveling

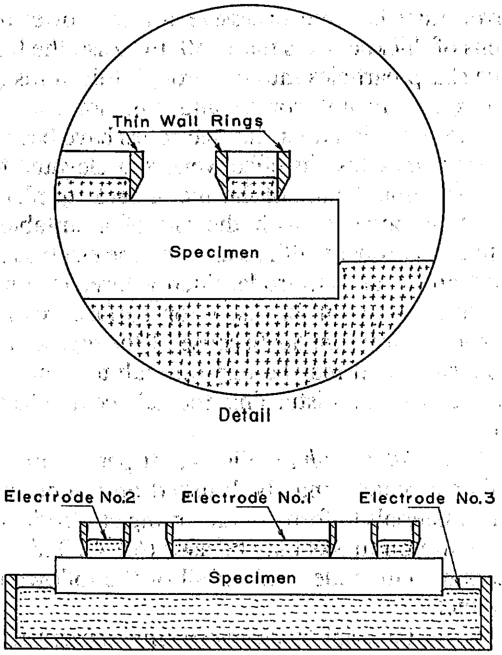


A—Plate Specimen



B—Tube or Rod Specimen

FIG. 6 Conducting-Paint Electrodes



NOTE: **Caution**—See 6.1.8

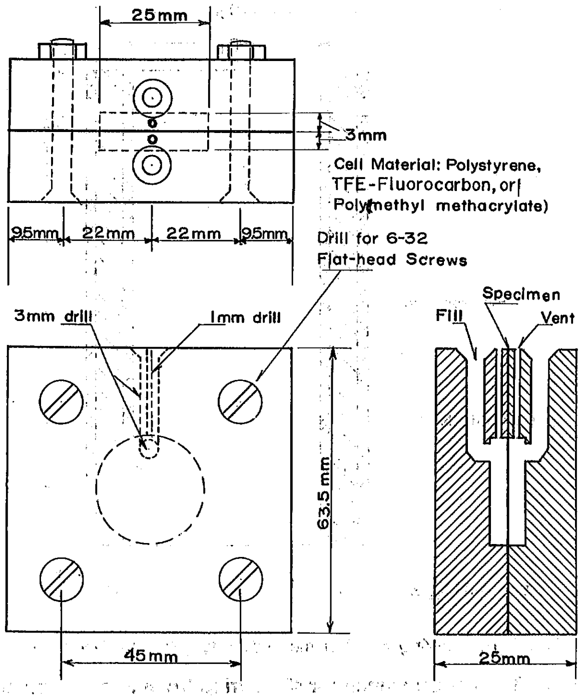
FIG. 7A Mercury Electrodes for Flat, Solid Specimens

on the side away from the liquid metal. Figs. 7A and 7B show two electrode arrangements.

NOTE 1: **Caution**—Mercury metal vapor poisoning has long been recognized as a hazard in industry. The maximum exposure limits are set by the American Conference of Governmental Industrial Hygienists.[6] The concentration of mercury vapor over spills from broken thermometers, barometers, or other instruments using mercury can easily exceed these exposure limits. Mercury, being a liquid and quite heavy, will disintegrate into small droplets and seep into cracks and crevices in the floor. The use of a commercially available emergency spill kit is recommended whenever a spill occurs. The increased area of exposure adds significantly to the mercury vapor concentration in air. Mercury vapor concentration is easily monitored using commercially available sniffers. Spot checks should be made periodically around operations where mercury is exposed to the atmosphere. Thorough checks should be made after spills.

6.1.9 *Flat Metal Plates,* Fig. 4, (preferably guarded) may be used for testing flexible and compressible materials, both at room temperature and at elevated temperatures. They may be circular or rectangular (for tapes). To ensure intimate contact with the specimen, considerable pressure is usually required. Pressures of 140 to 700 kPa have been found satisfactory (see material specifications).

6.1.10 *Conducting Rubber* has been used as electrode material, as in Fig. 4, and has the advantage that it can quickly and easily be applied and removed from the specimen. As the electrodes are applied only during the time of measurement, they do not interfere with the conditioning of the specimen. The conductive-rubber material must be backed by proper plates and be soft enough so that effective contact with the specimen is obtained when a reasonable pressure is applied.


25mm
3mm
Cell Material: Polystyrene, TFE-Fluorocarbon, or Polymethyl methacrylate)
9.5mm
22mm
22mm
9.5mm
Drill for 6-32 Flat-head Screws
3mm drill
1mm drill
63.5 mm
45mm
Specimen
Fill
Vent
25mm

NOTE: **Caution**—See 6.1.8

FIG. 7B Mercury Cell for Thin Sheet Material

NOTE 2—There is evidence that values of conductivity obtained using conductive-rubber electrodes are always smaller (20 to 70 %) than values obtained with tinfoil electrodes (6). When only order-of-magnitude accuracies are required, and these contact errors can be neglected, a properly designed set of conductive-rubber electrodes can provide a rapid means for making conductivity and resistivity determinations.

6.1.11 *Water* is widely employed as one electrode in testing insulation on wires and cables. Both ends of the specimen must be out of the water and of such length that leakage along the insulation is negligible. Guard rings may be necessary at each end. It may be desirable to add a small amount of sodium chloride to the water to ensure high conductivity. Measurements may be performed at temperatures up to about 100°C.

7. Choice of Apparatus and Test Method

7.1 *Power Supply*—A source of very steady direct voltage is required (see X1.7.3). Batteries or other stable direct voltage supplies may be used.

7.2 *Guard Circuit*—Whether measuring resistance of an insulating material with two electrodes (no guard) or with a three-terminal system (two electrodes plus guard), consider how the electrical connections are made between the test instrument and the test sample. If the test specimen is at some distance from the test instrument, or the test specimen is tested under humid conditions, or if a relatively high (10^{10} to 10^{15} ohms) specimen resistance is expected, spurious resistance paths can easily exist between the test instrument and test specimen. A guard circuit is necessary to minimize interference from these spurious paths. (See also Appendix X1.9)

7.2.1 *With Guard Electrode*—Use coaxial cable, with the core lead to the guarded electrode and the shield to the guard

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[6] American Conference of Governmental and Industrial Hygienists, P.O. 1937, Cincinnati, OH, 45201.

TABLE 1 Apparatus and Conditions for Use

Method	Reference		Maximum Ohms Detectable at 500 V	Maximum Ohms Measurable to ±6 % at 500 V	Type of Measurement	Ohms Shunted by Insulation Resistance from Guard to Guarded Electrode
	Section	Figure				
Voltmeter-ammeter (galvanometer)	X3.1	X1	10^{12}	10^{11}	deflection	10 to 10^5
Comparison (galvanometer)	X3.4	X3	10^{12}	10^{11}	deflection	10 to 10^5
Voltmeter-ammeter (d-c amplification, electrometer)	X3.2	X2(*a*)	10^{15}	10^{13}	deflection	10^2 to 10^9
		(Position *1*)				
		X2(*a*)	10^{15}	10^{13}	deflection	10^2 to 10^3
		(Position *2*)	10^{17}	10^{15}	deflection	10^3 to 10^{11}
		X2(*b*)	10^{17}	10^{15}	null	0 (effective)
		X2(*b*)				
Comparison (Wheatstone bridge)	X3.5	X4	10^{15}	10^{14}	null	10^5 to 10^6
Voltage rate-of-change	X3.3	X5	~100 MΩ·F		deflection	unguarded
Megohmmeter (typical)	commercial instruments		10^{15}	10^{14}	direct-reading	10^4 to 10^{10}

electrode, to make adequate guarded connections between the test equipment and test specimen. Coaxial cable (again with the shield tied back to the guard) for the unguarded lead is not mandatory here (or in 7.2.2), although its use provides some reduction in background noise. (See also Fig. 8)

7.2.2 *Without Guard Electrode*—Use coaxial cable, with the core lead to one electrode and the shield terminated about 1 cm from the end of the core lead. (See also Fig. 9)

7.3 *Direct Measurements*—The current through a specimen at a fixed voltage may be measured using any equipment that has the required sensitivity and accuracy (±10 % is usually adequate). Current-measuring devices available include electrometers, d-c amplifiers with indicating meters, and galvanometers. Typical methods and circuits are given in Appendix X3. When the measuring device scale is calibrated to read ohms directly no calculations are required.

7.4 *Comparison Methods*—A Wheatstone-bridge circuit may be used to compare the resistance of the specimen with that of a standard resistor (see Appendix X3).

7.5 *Precision and Bias Considerations:*

7.5.1 *General*—As a guide in the choice of apparatus, the pertinent considerations are summarized in Table 1, but it is not implied that the examples enumerated are the only ones applicable. This table is not intended to indicate the limits of sensitivity and error of the various methods *per se*, but rather is intended to indicate limits that are distinctly possible with modern apparatus. In any case, such limits can be achieved or exceeded only through careful selection and combination of the apparatus employed. It must be emphasized, however, that the errors considered are those of instrumentation only. Errors such as those discussed in Appendix X1 are an

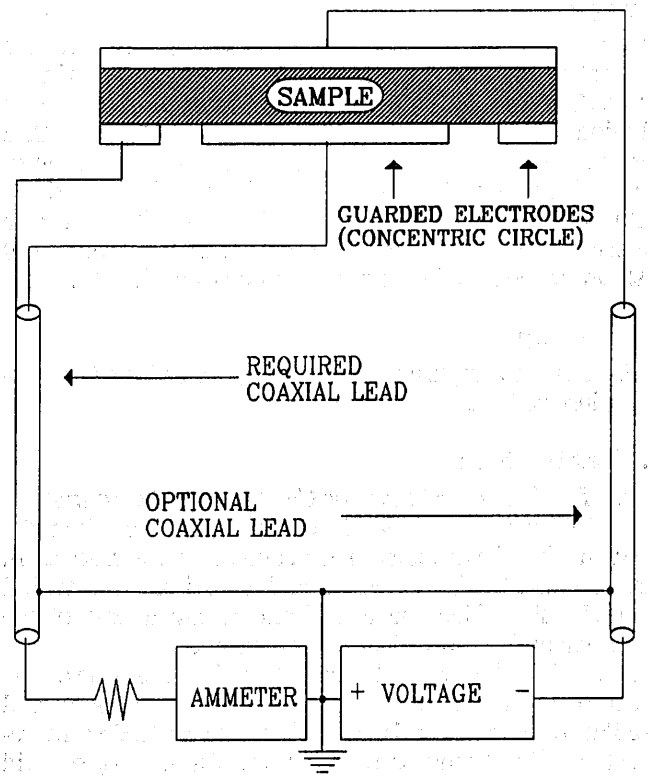


FIG. 8 Connections to Guarded Electrode for Volume and Surface Resistivity Measurements (Volume Resistance hook-up shown)

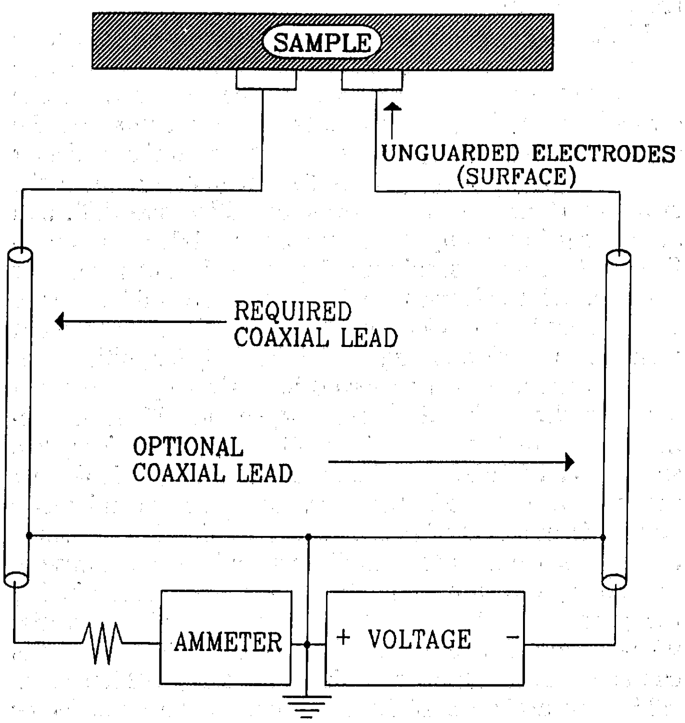


FIG. 9 Connections to Unguarded Electrodes for Unguarded Surface Measurements

entirely different matter. In this latter connection, the last column of Table 1 lists the resistance that is shunted by the insulation resistance between the guarded electrode and the guard system for the various methods. In general, the lower such resistance, the less probability of error from undue shunting.

NOTE 3—No matter what measurement method is employed, the highest precisions are achieved only with careful evaluation of all sources of error. It is possible either to set up any of these methods from the component parts, or to acquire a completely integrated apparatus. In general, the methods using high-sensitivity galvanometers require a more permanent installation than those using indicating meters or recorders. The methods using indicating devices such as voltmeters, galvanometers, d-c amplifiers, and electrometers require the minimum of manual adjustment and are easy to read but the operator is required to make the reading at a particular time. The Wheatstone bridge (Fig. X.1.4) and the potentiometer method (Fig. X.1.2(*b*)), require the undivided attention of the operator in keeping a balance, but allow the setting at a particular time to be read at leisure.

7.5.2 *Direct Measurements:*

7.5.2.1 *Galvanometer-Voltmeter*—The maximum percentage error in the measurement of resistance by the galvanometer-voltmeter method is the sum of the percentage errors of galvanometer indication, galvanometer readability, and voltmeter indication. As an example: a galvanometer having a sensitivity of 500 pA/scale division will be deflected 25 divisions with 500 V applied to a resistance of 40 GΩ (conductance of 25 pS). If the deflection can be read to the nearest 0.5 division, and the calibration error (including Ayrton Shunt error) is ±2 % of the observed value, the resultant galvanometer error will not exceed ±4 %. If the voltmeter has an error of ±2 % of full scale, this resistance can be measured with a maximum error of ±6 % when the voltmeter reads full scale, and ±10 % when it reads one third full scale. The desirability of readings near full scale are readily apparent.

7.5.2.2 *Voltmeter-Ammeter*—The maximum percentage error in the computed value is the sum of the percentage errors in the voltages, V_x and V_s, and the resistance, R_s. The errors in V_s and R_s are generally dependent more on the characteristics of the apparatus used than on the particular method. The most significant factors that determine the errors in V_s are indicator errors, amplifier zero drift, and amplifier gain stability. With modern, well-designed amplifiers or electrometers, gain stability is usually not a matter of concern. With existing techniques, the zero drift of direct voltage amplifiers or electrometers cannot be eliminated but it can be made slow enough to be relatively insignificant for these measurements. The zero drift is virtually nonexistent for carefully designed converter-type amplifiers. Consequently, the null method of Fig. X1.2(*b*) is theoretically less subject to error than those methods employing an indicating instrument, provided, however, that the potentiometer voltage is accurately known. The error in R_s is to some extent dependent on the amplifier sensitivity. For measurement of a given current, the higher the amplifier sensitivity, the greater likelihood that lower valued, highly precise wire-wound standard resistors can be used. Such amplifiers can be obtained. Standard resistances of 100 GΩ known to ±2 %, are available. If 10-mV input to the amplifier or electrometer gives full-scale deflection with an error not greater than 2 % of full scale, with 500 V applied, a resistance of 5000 TΩ can be measured with a maximum error of 6 % when the voltmeter reads full scale, and 10 % when it reads ⅓ scale.

7.5.2.3 *Comparison-Galvanometer*—The maximum percentage error in the computed resistance or conductance is given by the sum of the percentage errors in R_s, the galvanometer deflections or amplifier readings, and the assumption that the current sensitivities are independent of the deflections. The latter assumption is correct to well within ±2 % over the useful range (above 1/10 full-scale deflection) of a good, modern galvanometer (probably ⅓ scale deflection for a d-c current amplifier). The error in R_s depends on the type of resistor used, but resistances of 1 MΩ with a limit of error as low as 0.1 % are available. With a galvanometer or d-c current amplifier having a sensitivity of 10 nA for full-scale deflection, 500 V applied to a resistance of 5 TΩ will produce a 1 % deflection. At this voltage, with the above noted standard resistor, and with $F_s = 10^5$, d_s would be about half of full-scale deflection, with a readability error not more than ±1 %. If d_x is approximately ¼ of full-scale deflection, the readability error would not exceed ±4 %, and a resistance of the order of 200 GΩ could be measured with a maximum error of ±5½ %.

7.5.2.4 *Voltage Rate-of-Change*—The accuracy of the measurement is directly proportional to the accuracy of the measurement of applied voltage and time rate of change of the electrometer reading. The length of time that the electrometer switch is open and the scale used should be such that the time can be measured accurately and a full-scale reading obtained. Under these conditions, the accuracy will be comparable with that of the other methods of measuring current.

7.5.2.5 *Comparison Bridge*—When the detector has adequate sensitivity, the maximum percentage error in the computer resistance is the sum of the percentage errors in the arms, *A, B,* and *N*. With a detector sensitivity of 1 mV/scale division, 500 V applied to the bridge, and R_N = 1 GΩ, a resistance of 1000 TΩ will produce a detector deflection of one scale division. Assuming negligible errors in R_A and R_B, with R_N = 1 GΩ known to within ±2 % and with the bridge balanced to one detector-scale division, a resistance of 100 TΩ can be measured with a maximum error of ±6 %.

8. Sampling

8.1 Refer to applicable materials specifications for sampling instructions.

9. Test Specimens

9.1 *Insulation Resistance or Conductance Determination:*

9.1.1 The measurement is of greatest value when the specimen has the form, electrodes, and mounting required in actual use. Bushings, cables, and capacitors are typical examples for which the test electrodes are a part of the specimen and its normal mounting means.

9.1.2 For solid materials, the test specimen may be of any practical form. The specimen forms most commonly used are flat plates, tapes, rods, and tubes. The electrode arrangements of Fig. 2 may be used for flat plates, rods, or rigid tubes whose inner diameter is about 20 mm or more. The electrode arrangement of Fig. 3 may be used for strips of sheet material or for flexible tape. For rigid strip specimens the metal support may not be required. The electrode arrangements of Fig. 6 may be used for flat plates, rods, or tubes. Comparison of materials when using different electrode arrangements is frequently inconclusive and should be avoided.

9.2 *Volume Resistance or Conductance Determination:*

9.2.1 The test specimen may have any practical form that allows the use of a third electrode, when necessary, to guard against error from surface effects. Test specimens may be in the form of flat plates, tapes, or tubes. Figs. 4 and 7 illustrate the application and arrangement of electrodes for plate or sheet specimens. Fig. 5 is a diametral cross section of three electrodes applied to a tubular specimen, in which electrode No. 1 is the guarded electrode, electrode No. 2 is a guard electrode consisting of a ring at each end of electrode No. 1, and electrode No. 3 is the unguarded electrode **(7, 8)**. For materials that have negligible surface leakage, the guard rings may be omitted. Convenient and generally suitable dimensions applicable to Fig. 4 in the case of test specimens that are 3 mm in thickness are as follows: $D_3 = 100$ mm, $D_2 = 88$ mm, and $D_1 = 76$ mm, or alternatively, $D_3 = 50$ mm, $D_2 = 38$ mm, and $D_1 = 25$ mm. For a given sensitivity, the larger specimen allows more accurate measurements on materials of higher resistivity.

9.2.2 Measure the average thickness of the specimens in accordance with one of the methods in Test Methods D 374 pertaining to the material being tested. The actual points of measurement shall be uniformly distributed over the area to be covered by the measuring electrodes.

9.2.3 It is not necessary that the electrodes have the circular symmetry shown in Fig. 4 although this is generally convenient. The guarded electrode (No. 1) may be circular, square, or rectangular, allowing ready computation of the guarded electrode area for volume resistivity or conductivity determination when such is desired. The diameter of a circular electrode, the side of a square, or the shortest side of a rectangular electrode, should be at least four times the specimen thickness. The gap width should be great enough so that the surface leakage between electrodes No. 1 and No. 2 does not cause an error in the measurement (this is particularly important for high-input-impedance instruments, such as electrometers). If the gap is made equal to twice the specimen thickness, as suggested in 9.3.3, so that the specimen can be used also for surface resistance or conductance determinations, the effective area of electrode No. 1 can be taken, usually with sufficient accuracy, as extending to the center of the gap. If, under special conditions, it becomes desirable to determine a more accurate value for the effective area of electrode No. 1, the correction for the gap width can be obtained from Appendix X2. Electrode No. 3 may have any shape provided that it extends at all points beyond the inner edge of electrode No. 2 by at least twice the specimen thickness.

9.2.4 For tubular specimens, electrode No. 1 should encircle the outside of the specimen and its axial length should be at least four times the specimen wall thickness. Considerations regarding the gap width are the same as those given in 9.2.3. Electrode No. 2 consists of an encircling electrode at each end of the tube, the two parts being electrically connected by external means. The axial length of each of these parts should be at least twice the wall thickness of the specimen. Electrode No. 3 must cover the inside surface of the specimen for an axial length extending beyond the outside gap edges by at least twice the wall thickness. The tubular specimen (Fig. 5) may take the form of an insulated wire or cable. If the length of electrode is more than 100 times the thickness of the insulation, the effects of the ends of the guarded electrode become negligible, and careful spacing of the guard electrodes is not required. Thus, the gap between electrodes No. 1 and No. 2 may be several centimetres to permit sufficient surface resistance between these electrodes when water is used as electrode No. 1. In this case, no correction is made for the gap width.

9.3 *Surface Resistance or Conductance Determination:*

9.3.1 The test specimen may be of any practical form consistent with the particular objective, such as flat plates, tapes, or tubes.

9.3.2 The arrangements of Figs. 2 and 3 were devised for those cases where the volume resistance is known to be high relative to that of the surface **(2)**. However, the combination of molded and machined surfaces makes the result obtained generally inconclusive for rigid strip specimens. The arrangement of Fig. 2 is somewhat more satisfactory when applied to specimens for which the width is much greater than the thickness, the cut edge effect thus tending to become relatively small. Hence, this arrangement is more suitable for testing thin specimens such as tape, than for testing relatively thicker specimens. The arrangements of Figs. 2 and 3 should never be used for resistance or conductance determinations without due considerations of the limitations noted above.

9.3.3 The three electrode arrangements of Figs. 4, 6 and 7 may be used for purposes of material comparison. The resistance or conductance of the surface gap between electrodes No. 1 and No. 2 is determined directly by using electrode No. 1 as the guarded electrode, electrode No. 3 as the guard electrode, and electrode No. 2 as the unguarded electrode **(7, 8)**. The resistance or conductance so determined is actually the resultant of the surface resistance or conductance between electrodes No. 1 and No. 2 in parallel with some volume resistance or conductance between the same two electrodes. For this arrangement the surface gap width, g, should be approximately twice the specimen thickness, t, except for thin specimens, where g may be much greater than twice the material thickness.

9.3.4 Special techniques and electrode dimensions may be required for very thin specimens having such a low volume resistivity that the resultant low resistance between the guarded electrode and the guard system would cause excessive error.

9.4 *Liquid Insulation Resistance*—The sampling of liquid insulating materials, the test cells employed, and the methods of cleaning the cells shall be in accordance with Test Method D 1169.

10. Specimen Mounting

10.1 In mounting the specimens for measurements, it is important that there shall be no conductive paths between the electrodes or between the measuring electrodes and ground that will have a significant effect on the reading of the measuring instrument **(9)**. Insulating surfaces should not be handled with bare fingers (acetate rayon gloves are recommended). For referee tests of volume resistivity or conductivity, the surfaces should be cleaned with a suitable solvent

TABLE 2 Calculation of Resistivity or Conductivity[A]

Type of Electrodes or Specimen	Volume Resistivity, Ω-cm		Volume Conductivity, S/cm
	$\rho_v = \frac{A}{t} R_v$		$\gamma_v = \frac{t}{A} G_v$
Circular (Fig. 4)		$A = \frac{\pi(D_1 + g)^2}{4}$	
Rectangular		$A = (a + g)(b + g)$	
Square		$A = (a + g)^2$	
Tubes (Fig. 5)		$A = \pi D_0 (L + g)$	
Cables	$\rho_v = \frac{2\pi L R_v}{\ln \frac{D_2}{D_1}}$		$\gamma_v = \frac{\ln \frac{D_2}{D_1}}{2\pi L R_v}$
	Surface Resistivity, Ω (per square)		Surface Conductivity, S (per square)
	$\rho_s = \frac{P}{g} R_s$		$\gamma_s = \frac{g}{P} G_s$
Circular (Fig. 4)		$P = \pi D_0$	
Rectangular		$P = 2(a + b + 2g)$	
Square		$P = 4(a + g)$	
Tubes (Figs. 5 and 6)		$P = 2 \pi D_2$	

Nomenclature:

A = the effective area of the measuring electrode for the particular arrangement employed,

P = the effective perimeter of the guarded electrode for the particular arrangement employed,

R_v = measured volume resistance in ohms,

G_v = measured volume conductance in siemens,

R_s = measured surface resistance in ohms,

G_s = measured surface conductance in siemens,

t = average thickness of the specimen,

D_0, D_1, D_2, g, L = dimensions indicated in Figs. 4 and 6 (see Appendix X2 for correction to g),

$a, b,$ = lengths of the sides of rectangular electrodes, and

ln = natural logarithm.

[A] All dimensions are in centimetres.

before conditioning. When surface resistance is to be measured, the surfaces should be cleaned or not cleaned as specified or agreed upon.

11. Conditioning

11.1 The specimens shall be conditioned in accordance with Methods D 618.

11.2 Circulating-air environmental chambers or the methods described in Practice E 104 may be used for controlling the relative humidity.

12. Procedure

12.1 *Insulation Resistance or Conductance*—Properly mount the specimen in the test chamber. If the test chamber and the conditioning chamber are the same (recommended procedure), the specimens should be mounted before the conditioning is started. Make the measurement with a suitable device having the required sensitivity and accuracy (see Appendix X3). Unless otherwise specified, the time of electrification shall be 60 s, and the applied direct voltage shall be 500 ± 5 V.

12.2 *Volume Resistivity or Conductivity*—Measure the dimensions of the electrodes and width of guard gap, g. Make the measurement with a suitable device having the required sensitivity and accuracy. Unless otherwise specified, the time of electrification shall be 60 s, and the applied direct voltage shall be 500 ± 5 V.

12.3 *Surface Resistance or Conductance:*

12.3.1 Measure the electrode dimensions and the distance between the electrodes, g. Measure the surface resistance or conductance between electrodes No. 1 and 2 with a suitable device having the required sensitivity and accuracy. Unless otherwise specified, the time of electrification shall be 60 s, and the applied direct voltage shall be 500 ± 5 V.

12.3.2 When the electrode arrangement of Fig. 2 is used, P is taken as the perimeter of the cross section of the specimen. For thin specimens, such as tapes, this perimeter effectively reduces to twice the specimen width.

12.3.3 When the electrode arrangements of Fig. 6 are used (and the volume resistance is known to be high compared to the surface resistance), P is taken to be the length of the electrodes or circumference of the cylinder.

13. Calculation

13.1 Calculate the volume resistivity, ρ_v, and the volume conductivity, γ_v, using the equations in Table 2.

13.2 Calculate the surface resistivity, ρ_s, and the surface conductivity, γ_s, using the equations in Table 2.

14. Report

14.1 Report the following information:

14.1.1 A description and identification of the material (name, grade, color, manufacturer, etc.),

14.1.2 Shape and dimensions of the test specimen,

14.1.3 Type and dimensions of electrodes,

14.1.4 Conditioning of the specimen (cleaning, predrying, hours at humidity and temperature, etc.),

14.1.5 Test conditions (specimen temperature, relative humidity, etc., at time of measurement),

14.1.6 Method of measurement (see Appendix X3),

14.1.7 Applied voltage,

14.1.8 Time of electrification of measurement,

14.1.9 Measured values of the appropriate resistances in ohms or conductances in siemens, 14.1.10 Computed values when required, of volume resistivity in ohm-centimetres, volume conductivity in siemens per centimetre, surface resistivity in ohms (per square), or surface conductivity in siemens (per square), and

14.1.11 Statement as to whether the reported values are "apparent" or "steady-state."

15. Precision and Bias

15.1 Precision and bias are inherently affected by the choice of method, apparatus, and specimen. For analysis and details see Sections 7 and 9, and particularly 7.5.1 through 7.5.2.5.

REFERENCES

(1) Curtis, H. L., "Insulating Properties of Solid Dielectric." *Bulletin,* National Institute of Standards and Technology, Vol II, 1915, Scientific Paper No. 234, pp. 369–417.

(2) Field, R. F., "How Humidity Affects Insulation, Part I, D-C Phenomena," *General Radio Experimenter,* Vol 20, Nos. 2 and 3, July–August, 1945.

(3) Field, R. F., "The Formation of Ionized Water Films on Dielectrics Under Conditions of High Humidity," *Journal of Applied Physics,* Vol 5, May, 1946.

(4) Herou, R., and LaCoste, R., "Sur La Mesure Des Resistivities et L'Etude de Conditionnement des Isolantes en Feuilles," Report IEC 15-GT$_2$ (France) 4 April, 1963.

(5) Thompson, B. H., and Mathes, K. N., "Electrolytic Corrosion—Methods of Evaluating Materials Used in Tropical Service," *Transactions,* American Institute of Electrical Engineers, Vol 64, June, 1945, p. 287.

(6) Scott, A. H., "Anomalous Conductance Behavior in Polymers," Report of the 1965 Conference on Electrical Insulation, NRC-NAS.

(7) Amey, W. G., and Hamberger, F., Jr., "A Method for Evaluating the Surface and Volume Resistance Characteristics of Solid Dielectric Materials," *Proceedings,* Am. Soc. Testing Mats., Vol 49, 1949, pp. 1079–1091.

(8) Witt, R. K., Chapman, J. J., and Raskin, B. L., "Measuring of Surface and Volume Resistance," *Modern Plastics,* Vol 24, No. 8, April, 1947, p. 152.

(9) Scott, A. H., "Insulation Resistance Measurements," Fourth Electrical Insulation Conference, Washington, DC, Feb. 19–22, 1962.

(10) Kline, G. M., Martin, A. R., and Crouse, W. A., "Sorption of Water by Plastics," *Proceedings,* Am. Soc. Testing Mats., Vol 40, 1940, pp. 1273–1282.

(11) Greenfield, E. W., "Insulation Resistance Measurements," *Electrical Engineering,* Vol 66. July, 1947, pp. 698–703.

(12) Cole, K. S., and Cole, R. H., "Dispersion and Absorption in Dielectrics, II Direct Current Characteristics," *Journal of Chemical Physics,* Vol 10, 1942.

(13) Field, R. F., "Interpretation of Current-Time Curves as Applied to Insulation Testing," AIEE Boston District Meeting, April 19–20, 1944.

(14) Lauritzen, J. I., "The Effective Area of a Guarded Electrode," *Annual Report,* Conference on Electrical Insulation. NAS-NRC Publication 1141, 1963.

(15) Turner, E. F., Brancato, E. L., and Price, W., "The Measurement of Insulation Conductivity." *NRL Report 5060,* Naval Research Laboratory, Feb. 25, 1958.

(16) Dorcas, D. S., and Scott, R. N., "Instrumentation for Measuring the D-C Conductivity of Very High Resistivity Materials," *Review of Scientific Instruments,* Vol 35, No. 9, Sept. 1964.

(17) Endicott, H. S., "Insulation Resistance, Absorption, and Their Measurement," *Annual Report,* Conference on Electrical Insulation, NAS-NRC Publication, 1958.

(18) Occhini, E. and Maschio, G., "Electrical Characteristics of Oil-Impregnated Paper as Insulation for HV-DC Cables," *IEEE Transactions on Power Apparatus and Systems,* Vol PAS-86, No. 3- March 1967.

(19) Endicott, H. S., "Guard-Gap Correction for Guarded-Electrode Measurements and Exact Equations for the Two-Fluid Method of Measuring Permittivity and Loss," *Journal of Testing and Evaluation, JTEVA,* Vol 4, No. 3, May 1976, pp. 188–195.

APPENDIXES

(Nonmandatory Information)

X1. FACTORS AFFECTING INSULATION RESISTANCE OR CONDUCTANCE MEASUREMENTS

X1.1 *Inherent Variation in Materials*—Because of the variability of the resistance of a given specimen under similar test conditions and the nonuniformity of the same material from specimen to specimen, determinations are usually not reproducible to closer than 10 % and often are even more widely divergent (a range of values of 10 to 1 may be obtained under apparently identical conditions).

X1.2 *Temperature*—The resistance of electrical insulating materials is known to change with temperature, and the variation often can be represented by a function of the form: **(18)**

$$R = Be^{m/T} \qquad \text{(X1)}$$

where:

R = resistance (or resistivity) of an insulating material or system,

B = proportionality constant,

m = activation constant, and

T = absolute temperature in kelvin (K).

This equation is a simplified form of the Arrhenius equation relating the activation energy of a chemical reaction to the absolute temperature; and the Boltzmann principle, a general law dealing with the statistical distribution of energy among large numbers of minute particles subject to thermal agitation. The activation constant, m, has a value that is characteristic of a particular energy absorption process. Several such processes may exist within the material, each with a different effective temperature range, so that several values of m would be needed to fully characterize the material. These values of m can be determined experimentally by plotting the natural logarithm of resistance against the reciprocal of the absolute temperature. The desired values of m are obtained from such a plot by measuring the slopes of the straight-line sections of the plot. This derives from Eq (1), for it follows that by taking the natural logarithm of both sides:

$$\ln R = \ln B + m \frac{1}{T} \qquad \text{(X2)}$$

The change in resistance (or resistivity) corresponding to a change in absolute temperature from T_1 to T_2, based on Eq 1, and expressed in logarithmic form, is:

$$\ln (R_2/R_1) = m \left(\frac{1}{T_2} - \frac{1}{T_1}\right) = m \left(\frac{\Delta T}{T_1 T_2}\right) \qquad \text{(X3)}$$

These equations are valid over a temperature range only if the material does not undergo a transition within this temperature range. Extrapolations are seldom safe since transitions are seldom obvious or predictable. As a corollary, deviation of a plot of the logarithm of R against $1/T$ from a straight line is evidence that a transition is occurring. Furthermore, in making comparisons between materials, it is essential that measurements be made over the entire range of interest for all materials.

NOTE X1—The resistance of an electrical insulating material may be affected by the time of temperature exposure. Therefore, equivalent temperature conditioning periods are essential for comparative measurements.

NOTE X2—If the insulating material shows signs of deterioration after conditioning at elevated temperatures, this information must be included with the test data.

X1.3 *Temperature and Humidity*—The insulation resistance of solid dielectric materials decreases both with increasing temperature as described in X1.2 and with increasing humidity (**1, 2, 3, 4**). Volume resistance is particularly sensitive to temperature changes, while surface resistance changes widely and very rapidly with humidity changes (**2, 3**). In both cases the change is exponential. For some materials a change from 25 to 100°C may change insulation resistance or conductance by a factor of 100 000, often due to the combined effects of temperature and moisture content change; the effect of temperature change alone is usually much smaller. A change from 25 to 90 % relative humidity may change insulation resistance or conductance by as much as a factor of 1 000 000 or more. Insulation resistance or conductance is a function of both the volume and surface resistance or conductance of the specimen, and surface resistance changes almost instantaneously with change of relative humidity. It is, therefore, absolutely essential to maintain both temperature and relative humidity within close limits during the conditioning period and to make the insulation resistance or conductance measurements in the specified conditioning environment. Another point not to be overlooked is that at relative humidities above 90 %, surface condensation may result from inadvertant fluctuations in humidity or temperature produced by the conditioning system. This problem can be avoided by the use of equivalent absolute humidity at a slightly higher temperature, as equilibrium moisture content remains nearly the same for a small temperature change. In determining the effect of humidity on volume resistance or conductance, extended periods of conditioning are required, since the absorption of water into the body of the dielectric is a relatively slow process (**10**). Some specimens require months to come to equilibrium. When such long periods of conditioning are prohibitive, use of thinner specimens or comparative measurements near equilibrium may be reasonable alternatives, but the details must be included in the test report.

X1.4 *Time of Electrification*—Measurement of a dielectric material is not fundamentally different from that of a conductor except that an additional parameter, time of electrification, (and in some cases the voltage gradient) is involved. The relationship between the applied voltage and the current is involved in both cases. For dielectric materials, the standard resistance placed in series with the unknown resistance must have a relatively low value, so that essentially full voltage will be applied across the unknown resistance. When a potential difference is applied to a specimen, the current through it generally decreases asymptotically toward a limiting value which may be less than 0.01 of the current observed at the end of 1 min (**9, 11**). This decrease of current with time is due to dielectric absorption (interfacial polarization, volume charge, etc.) and the sweep of mobile ions to the electrodes. In general, the relation of current and time is of the form $I(t) = At^{-m}$, after the initial charge is completed and until the true leakage current becomes a significant factor (**12, 13**). In this relation A is a constant, numerically the current at unit time, and m usually, but not always, has a value between 0 and 1. Depending upon the characteristics of the specimen material, the time required for the current to decrease to within 1 % of this minimum value may be from a few seconds to many hours. Thus, in order to ensure that measurements on a given material will be comparable, it is necessary to specify the time of electrification. The conventional arbitrary time of electrification has been 1 min. For some materials, misleading conclusions may be drawn from the test results obtained at this arbitrary time. A resistance-time or conductance-time curve should be obtained under the conditions of test for a given material as a basis for selection of a suitable time of electrification, which must be specified in the test method for that material, or such curves should be used for comparative purposes. Occasionally, a material will be found for which the current increases with time. In this case either the time curves must be used or a special study undertaken, and arbitrary decisions made as to the time of electrification.

X1.5 *Magnitude of Voltage:*

X1.5.1 Both volume and surface resistance or conductance of a specimen may be voltage-sensitive (**4**). In that case, it is necessary that the same voltage gradient be used if measurements on similar specimens are to be comparable. Also, the applied voltage should be within at least 5 % of the specified voltage. This is a separate requirement from that given in X1.7.3, which discusses voltage regulation and stability where appreciable specimen capacitance is involved.

X1.5.2 Commonly specified test voltages to be applied to the complete specimen are 100, 250, 500, 1000, 2500, 5000, 10 000 and 15 000 V. Of these, the most frequently used are 100 and 500 V. The higher voltages are used either to study the voltage-resistance or voltage-conductance characteristics of materials (to make tests at or near the operating voltage gradients), or to increase the sensitivity of measurement.

X1.5.3 Specimen resistance or conductance of some materials may, depending upon the moisture content, be affected by the polarity of the applied voltage. This effect, caused by electrolysis or ionic migration, or both, particularly in the presence of nonuniform fields, may be particularly noticeable in insulation configurations such as those found in cables where the test-voltage gradient is greater at the inner conductor than at the outer surface. Where electrolysis or ionic migration does exist in specimens, the electrical resistance will be lower when the smaller test electrode is made negative with respect to the larger. In such cases, the polarity of the applied voltage shall be specified according to the requirements of the specimen under test.

X1.6 *Contour of Specimen:*

X1.6.1 The measured value of the insulation resistance or conductance of a specimen results from the composite effect of its volume and surface resistances or conductances. Since the relative values of the components vary from material to material, comparison of different materials by the use of the electrode systems of Figs. 1, 2, and 3 is generally inconclusive. There is no assurance that, if material A has a higher insulation resistance than material B as measured by the use of one of these electrode systems, it will also have a higher resistance than B in the application for which it is intended.

X1.6.2 It is possible to devise specimen and electrode configurations suitable for the separate evaluation of the volume resistance or conductance and the approximate surface resistance or conductance of the same specimen. In general, this requires at least three electrodes so arranged that one may select electrode pairs for which the resistance or conductance measured is primarily that of either a volume current path or a surface current path, not both **(7)**.

X1.7 *Deficiencies in the Measuring Circuit:*

X1.7.1 The insulation resistance of many solid dielectric specimens is extremely high at standard laboratory conditions, approaching or exceeding the maximum measurable limits given in Table 1. Unless extreme care is taken with the insulation of the measuring circuit, the values obtained are more a measure of apparatus limitations than of the material itself. Thus errors in the measurement of the specimen may arise from undue shunting of the specimen, reference resistors, or the current-measuring device, by leakage resistances or conductances of unknown, and possibly variable, magnitude.

X1.7.2 Electrolytic, contact, or thermal emf's may exist in the measuring circuit itself; or spurious emf's may be caused by leakage from external sources. Thermal emf's are normally insignificant except in the low resistance circuit of a galvanometer and shunt. When thermal emf's are present, random drifts in the galvanometer zero occur. Slow drifts due to air currents may be troublesome. Electrolytic emf's are usually associated with moist specimens and dissimilar metals, but emf's of 20 mV or more can be obtained in the guard circuit of a high-resistance detector when pieces of the same metal are in contact with moist specimens. If a voltage is applied between the guard and the guarded electrodes a polarization emf may remain after the voltage is removed. True contact emf's can be detected only with an electrometer and are not a source of error. The term "spurious emf" is sometimes applied to electrolytic emf's. To ensure the absence of spurious emf's of whatever origin, the deflection of the detecting device should be observed before the application of voltage to the specimen and after the voltage has been removed. If the two deflections are the same, or nearly the same, a correction can be made to the measured resistance or conductance, provided the correction is small. If the deflections differ widely, or approach the deflection of the measurement, it will be necessary to find and eliminate the source of the spurious emf **(5)**. Capacitance changes in the connecting shielded cables can cause serious difficulties.

X1.7.3 Where appreciable specimen capacitance is involved, both the regulation and transient stability of the applied voltage should be such that resistance or conductance measurements can be made to prescribed accuracy. Short-time transients, as well as relatively long-time drifts in the applied voltage may cause spurious capacitive charge and discharge currents which can significantly affect the accuracy of measurement. In the case of current-measuring methods particularly, this can be a serious problem. The current in the measuring instrument due to a voltage transient is $I_0 = C_x dV/dt$. The amplitude and rate of pointer excursions depend upon the following factors:

X1.7.3.1 The capacitance of the specimen,

X1.7.3.2 The magnitude of the current being measured,

X1.7.3.3 The magnitude and duration of the incoming voltage transient, and its rate of change,

X1.7.3.4 The ability of the stabilizing circuit used to provide a constant voltage with incoming transients of various characteristics, and

X1.7.3.5 The time-constant of the complete test circuit as compared to the period and damping of the current-measuring instrument.

X1.7.4 Changes of range of a current-measuring instrument may introduce a current transient. When $R_m \ll R_x$ and $C_m \ll C_x$, the equation of this transient is

$$I = (V_0/R_x)[I - e^{-t/R_mC_x}] \qquad \text{(X4)}$$

where:

V_0 = applied voltage,
R_x = apparent resistance of the specimen,
R_m = effective input resistance of the measuring instrument,
C_x = capacitance of the specimen at 1000 Hz,
C_m = input capacitance of the measuring instrument, and
t = time after R_m is switched into the circuit.

For not more than 5 % error due to this transient,

$$R_mC_x \leqq t/3 \qquad \text{(X5)}$$

Microammeters employing feedback are usually free of this source of error as the actual input resistance is divided, effectively, by the amount of feedback, usually at least by 1000.

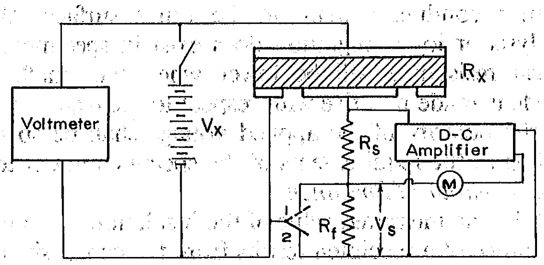
X1.8 *Residual Charge*—In X1.4 it was pointed out that the current continues for a long time after the application of a potential difference to the electrodes. Conversely, current will continue for a long time after the electrodes of a charged specimen are connected together. It should be established that the test specimen is completely discharged before attempting the first measurement, a repeat measurement, a measurement of volume resistance following a measurement of surface resistance, or a measurement with reversed voltage **(9)**. The time of discharge before making a measurement should be at least four times any previous charging time. The specimen electrodes should be connected together until the measurement is to be made to prevent any build-up of charge from the surroundings.

X1.9 *Guarding:*

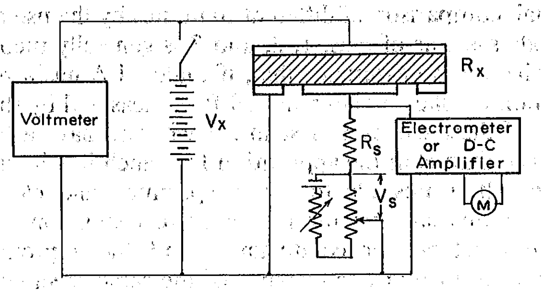
X1.9.1 Guarding depends on interposing, in all critical insulated paths, guard conductors which intercept all stray currents that might otherwise cause errors. The guard conductors are connected together, constituting the guard system and forming, with the measuring terminals, a three-terminal network. When suitable connections are made, stray currents from spurious external voltages are shunted away from the measuring circuit by the guard system.

X1.9.2 Proper use of the guard system for the methods involving current measurement is illustrated in Figs. X1.1 to X1.3, inclusive, where the guard system is shown connected to the junction of the voltage source and current-measuring instrument or standard resistor. In Fig. X1.4 for the Wheatstone-bridge method, the guard system is shown connected to the junction of the two lower-valued-resistance arms. In all cases, to be effective, guarding must be complete, and must include any controls operated by the observer in making the measurement. The guard system is generally maintained at a potential close to that of the guarded terminal, but insulated from it. This is because, among other things, the resistance of many insulating materials is voltage-dependent. Otherwise, the direct resistances or conductances of a three-terminal network are independent of the electrode potentials. It is usual to ground the guard system and hence one side of the voltage source and current-measuring device. This places both terminals of the specimen above ground. Sometimes, one terminal of the specimen is permanently grounded. The current-measuring device usually is then connected to this terminal, requiring that the voltage source be well insulated from ground.

X1.9.3 Errors in current measurements may result from the fact that the current-measuring device is shunted by the resistance or conductance between the guarded terminal and the guard system. This resistance should be at least 10 to 100 times the input resistance of the current measuring device. In some bridge techniques, the guard and measuring terminals are brought to nearly the same potentials, but a standard resistor in the bridge is shunted between the unguarded terminal and the guard system. This resistance should be at least 1000 times that of the reference resistor.



(a) Normal Use of Amplifier and Indicating Meter



(b) Amplifier and Indicating Meter as Null Detector

FIG. X1.2 Voltmeter-Ammeter Method Using D-C Amplification

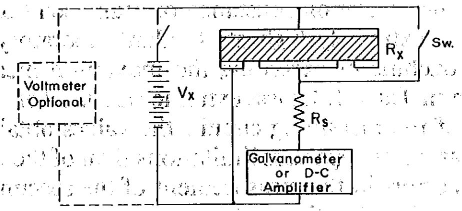


FIG. X1.3 Comparison Method Using a Galvanometer

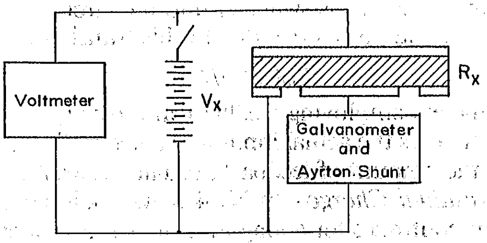


FIG. X1.1 Voltmeter-Ammeter Method Using a Galvanometer

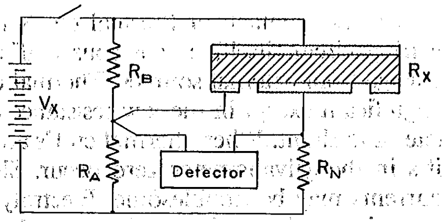


FIG. X1.4 Comparison Method Using a Wheatstone Bridge

X2. EFFECTIVE AREA OF GUARDED ELECTRODE

X2.1 *General*—Calculation of volume resistivity from the measured volume resistance involves the quantity *A*, the effective area of the guarded electrode. Depending on the material properties and the electrode configuration, *A* differs from the actual area of the guarded electrode for either, or both, of the following reasons.

X2.1.1 Fringing of the lines of current in the region of the electrode edges may effectively increase the electrode dimensions.

X2.1.2 If plane electrodes are not parallel, or if tubular electrodes are not coaxial, the current density in the specimen will not be uniform, and an error may result. This error is usually small and may be ignored.

X2.2 *Fringing:*

X2.2.1 If the specimen material is homogeneous and isotropic, fringing effectively extends the guarded electrode edge by an amount **(14, 19)**:

$$(g/2) - \delta \qquad \text{(X6)}$$

where:

$$\delta = t\{(2/\pi) \ln \cosh [(\pi/4)(g/t)]\},$$

and g and t are the dimensions indicated in Figs. 4 and 6. The correction may also be written

$$g[1 - (2\delta/g)] = Bg \qquad \text{(X7)}$$

where B is the fraction of the gap width to be added to the diameter of circular electrodes or to the dimensions of rectangular or cylindrical electrodes.

X2.2.2 Laminated materials, however, are somewhat anisotropic after volume absorption of moisture. Volume resistivity parallel to the laminations is then lower than that in the perpendicular direction, and the fringing effect is increased. With such moist laminates, δ approaches zero, and the guarded electrode effectively extends to the center of the gap between guarded and unguarded electrodes **(14)**.

X2.2.3 The fraction of the gap width g to be added to the diameter of circular electrodes or to the electrode dimensions of rectangular or cylindrical electrodes, B, as determined by above equation for δ, is as follows:

g/t	B	g/t	B
0.1	0.96	1.0	0.64
0.2	0.92	1.2	0.59
0.3	0.88	1.5	0.51
0.4	0.85	2.0	0.41
0.5	0.81	2.5	0.34
0.6	0.77	3.0	0.29
0.8	0.71		

NOTE X3—The symbol "ln" designates logarithm to the base e = 2.718. . . . When g is approximately equal to $2t$, δ is determined with sufficient approximation by the equation:

$$\delta = 0.586t$$

NOTE X4—For tests on thin films when $t \ll g$, or when a guard electrode is not used and one electrode extends beyond the other by a distance which is large compared with t, $0.883t$ should be added to the diameter of circular electrodes or to the dimensions of rectangular electrodes.

NOTE X5—During the transition between complete dryness and subsequent relatively uniform volume distribution of moisture, a laminate is neither homogeneous nor isotropic. Volume resistivity is of questionable significance during this transition and accurate equations are neither possible nor justified, calculations within an order of magnitude being more than sufficient.

X3. TYPICAL MEASUREMENT METHODS

X3.1 *Voltmeter-Ammeter Method Using a Galvanometer:*

X3.1.1 A d-c voltmeter and a galvanometer with a suitable shunt are connected to the voltage source and to the test specimen as shown in Fig. X1. The applied voltage is measured by a d-c voltmeter, having a range and accuracy that will give minimum error in voltage indication. In no case shall a voltmeter be used that has an error greater than ±2 % of full scale, nor a range such that the deflection is less than one third of full scale (for a pivot-type instrument). The current is measured by a galvanometer having a high current sensitivity (a scale length of 0.5 m is assumed, as shorter scale lengths will lead to proportionately higher errors) and provided with a precision Ayrton universal shunt for so adjusting its deflection that the readability error does not, in general, exceed ±2 % of the observed value. The galvanometer should be calibrated to within ±2 %. Current can be read directly if the galvanometer is provided with an additional suitable fixed shunt.

X3.1.2 The unknown resistance, R_x, or conductance, G_x, is calculated as follows:

$$R_x = 1/G_x = V_x/I_x = V_x/KdF \qquad \text{(X8)}$$

where:

K = galvanometer sensitivity, in amperes per scale division,

d = deflection in scale divisions,

F = ratio of the total current, I_x, to the galvanometer current, and

V_x = applied voltage.

X3.2 *Voltmeter-Ammeter Method Using D-C Amplification or Electrometer:*

X3.2.1 The voltmeter-ammeter method can be extended to measure higher resistances by using d-c amplification or an electrometer to increase the sensitivity of the current measuring device **(6, 15, 16)**. Generally, but not necessarily, this is achieved only with some sacrifice in precision, depending on the apparatus used. The d-c voltmeter and the d-c amplifier or electrometer are connected to the voltage source and the specimen as illustrated in Fig. X1.2. The applied voltage is measured by a d-c voltmeter having the same characteristics as prescribed in X3.1.1. The current is measured in terms of the voltage drop across a standard resistance, R_s.

X3.2.2 In the circuit shown in Fig. X2(*a*) the specimen current, I_x, produces across the standard resistance, R_s, a voltage drop which is amplified by the d-c amplifier, and read on an indicating meter or galvanometer. The net gain of the amplifier usually is stabilized by means of a feedback resistance, R_f, from the output of the amplifier. The indicating meter can be calibrated to read directly in terms of the feedback voltage, V_f, which is determined from the known value of the resistance of R_f, and the feedback current passing through it. When the amplifier has sufficient intrinsic gain, the feedback voltage, V_s, differs from the voltage, I_xR_s, by a negligible amount. As shown in Fig. X1.2(*a*) the return lead from the voltage source, V_x, can be connected to either end of the feedback resistor, R_f. With the connection made to the

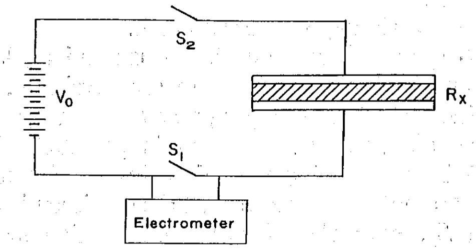


FIG. X3.1 Voltage Rate-of-Change Method

junction of R_s and R_f (switch in dotted position 1), the entire resistance of R_s is placed in the measuring circuit and any alternating voltage appearing across the specimen resistance is amplified only as much as the direct voltage $I_x R_s$, across R_s. With the connection made to the other end of R_f (switch position 2), the apparent resistance placed in the measuring circuit is R_s times the ratio of the degenerated gain to the intrinsic gain of the amplifier; any alternating voltage appearing across the specimen resistance is then amplified by the intrinsic amplifier gain.

X3.2.3 In the circuit shown in Fig. X1.2(*b*), the specimen current, I_x, produces a voltage drop across the standard resistance, R_s which may or may not be balanced out by adjustment of an opposing voltage, V_s, from a calibrated potentiometer. If no opposing voltage is used, the voltage drop across the standard resistance, R_s, is amplified by the d-c amplifier or electrometer and read on an indicating meter or galvanometer. This produces a voltage drop between the measuring electrode and the guard electrode which may cause an error in the current measurement unless the resistance between the measuring electrode and the guard electrode is at least 10 to 100 times that of R_s. If an opposing voltage, V_s, is used, the d-c amplifier or electrometer serves only as a very sensitive, high-resistance null detector. The return lead from the voltage source, V_x, is connected as shown, to include the potentiometer in the measuring circuit. When connections are made in this manner, no resistance is placed in the measuring circuit at balance and thus no voltage drop appears between the measuring electrode and the guard electrode. However, a steeply increasing fraction of R_s is included in the measuring circuit, as the potentiometer is moved off balance. Any alternating voltage appearing across the specimen resistance is amplified by the net amplifier gain. The amplifier may be either a direct voltage amplifier or an alternating voltage amplifier provided with input and output converters. Induced alternating voltages across the specimen often are sufficiently troublesome that a resistance-capacitance filter preceding the amplifier is required. The input resistance of this filter should be at least 100 times greater than the effect resistance that is placed in the measurement circuit by resistance R_s.

X3.2.4 The resistance, R_x, or the conductance, G_x, is calculated as follows:

$$R_x = 1/G_x = V_x/I_x = (V_x/V_s)R_s \tag{X9}$$

where:

V_x = applied voltage,
I_x = specimen current,
R_s = standard resistance, and
V_s = voltage drop across R_s, indicated by the amplifier output meter, the electrometer or the calibrated potentiometer.

X3.3 *Voltage Rate-of-Change Method:*

X3.3.1 If the specimen capacitance is relatively large, or capacitors are to be measured, the apparent resistant, R_x, can be determined from the charging voltage, V_0, the specimen capacitance value, C_0 (capacitance of C_x at 1000 Hz), and the rate-of-change of voltage, dV/dt, using the circuit of Fig. X3.1 **(17)**. To make a measurement the specimen is charged by closing S_2, with the electrometer shorting switch S_1 closed. When S_1 is subsequently opened, the voltage across the specimen will fall because the leakage and absorption currents must then be supplied by the capacitance C_0 rather than by V_0. The drop in voltage across the specimen will be shown by the electrometer. If a recorder is connected to the output of the electrometer, the rate of change of voltage, dV/dt, can be read from the recorder trace at any desired time after S_2 is closed (60 s usually specified). Alternatively, the voltage, ΔV, appearing on the electrometer in a time, Δt, can be used. Since this gives an average of the rate-of-change of voltage during Δt, the time Δt should be centered at the specified electrification time (time since closing S_2).

X3.3.2 If the input resistance of the electrometer is greater than the apparent specimen resistance and the input capacitance is 0.01 or less of that of the specimen, the apparent resistance at the time at which dV/dt or $\Delta V/\Delta t$ is determined is

$$R_x = V_0/I_x = V_0 dt/C_0 dV_m \text{ or, } V_0 \Delta t/C_0 \Delta V_m \tag{X10}$$

depending on whether or not a recorder is used. When the electrometer input resistance or capacitance cannot be ignored or when V_m is more than a small fraction of V_0 the complete equation should be used.

$$R_s = \{V_0[(R_x + R_m)/R_m]V_m\}/(C_0 + C_m)dV_m/dt \tag{X11}$$

where:

C_0 = capacitance of C_x at 1000 Hz,
R_m = input resistance of the electrometer,
C_m = input capacitance of the electrometer,
V_0 = applied voltage, and
V_m = electrometer reading = voltage decrease on C_x.

X3.4 *Comparison Method Using a Galvanometer or D-C Amplifier (1):*

X3.4.1 A standard resistance, R_s, and a galvanometer or d-c amplifier are connected to the voltage source and to the test specimen as shown in Fig. X3. The galvanometer and its associated Ayrton shunt is the same as described in X3.1.1. An amplifier of equivalent direct current sensitivity with an appropriate indicator may be used in place of the galvanometer. It is convenient, but not necessary, and not desirable if batteries are used as the voltage source (unless a high-input resistance voltmeter is used), to connect a voltmeter across the source for a continuous check of its voltage. The switch is provided for shorting the unknown resistance in the process of measurement. Sometimes provision is made to short either the unknown or standard resistance but not both at the same time.

X3.4.2 In general, it is preferable to leave the standard resistance in the circuit at all times to prevent damage to the current measuring instrument in case of specimen failure. With the shunt set to the least sensitive position and with the switch open, the voltage is applied. The Ayrton shunt is then adjusted to give as near maximum scale reading as possible. At the end of the electrification time the deflection, d_x, and the shunt ratio, F_x, are noted. The shunt is then set to the least sensitive position and the switch is closed to short the unknown resistance. Again the shunt is adjusted to give as near maximum scale reading as possible and the galvanometer or meter deflection, d_s, and the shunt ratio, F_s, are noted. It is assumed that the current sensitivities of the galvanometer or amplifier are equal for nearly equal deflections d_x and d_s.

X3.4.3 The unknown resistance, R_x, or conductance, G_x, is calculated as follows:

$$R = 1/G_x = R_s[(d_sF_s/d_xF_x) - 1] \qquad (X12)$$

where:

F_x and F_s = ratios of the total current to the galvanometer or d-c amplifier with R_x in the circuit, and shorted, respectively.

X3.4.4 In case R_s is shorted when R_x is in the circuit or the ratio of F_s to F_x is greater than 100, the value of R_x or G_x is computed as follows:

$$R_x = 1/G_x = R\ (d_sF_s/d_xF_x) \qquad (X13)$$

X3.5 *Comparison Methods Using a Wheatstone Bridge (2):*

X3.5.1 The test specimen is connected into one arm of a Wheatstone bridge as shown in Fig. X1.4. The three known arms shall be of as high resistance as practicable, limited by the errors inherent in such resistors. Usually, the lowest resistance, R_A, is used for convenient balance adjustment, with either R_B or R_N being changed in decade steps. The detector shall be a d-c amplifier, with an input resistance high compared to any of these arms.

X3.5.2 The unknown resistance, R_x, or conductance, G_x, is calculated as follows:

$$R_x = 1/G_x = R_BR_N/R_A \qquad (X14)$$

where R_A, R_B, and R_N are as shown in Fig. X1.4. When arm *A* is a rheostat, its dial can be calibrated to read directly in megohms after multiplying by the factor R_BR_N which for convenience can be varied in decade steps.

X3.6 *Recordings*—It is possible to record continuously against time the values of the unknown resistance or the corresponding value of current at a known voltage. Generally, this is accomplished by an adaptation of the voltmeter-ammeter method, using d-c amplification (X3.2). The zero drift of direct coupled d-c amplifiers, while slow enough for the measurements of X3.2, may be too fast for continuous recording. This problem can be resolved by periodic checks of the zero, or by using an a-c amplifier with input and output converter. The indicating meter of Fig. X1.2(*a*) can be replaced by a recording milliammeter or millivoltmeter as appropriate for the amplifier used. The recorder may be either the deflection type or the null-balance type, the latter usually having a smaller error. Null-balance-type recorders also can be employed to perform the function of automatically adjusting the potentiometer shown in Fig. X1.2(*b*) and thereby indicating and recording the quantity under measurement. The characteristics of amplifier, recorder balancing mechanism, and potentiometer can be made such as to constitute a well integrated, stable, electromechanical, feedback system of high sensitivity and low error. Such systems also can be arranged with the potentiometer fed from the same source of stable voltage as the specimen, thereby eliminating the voltmeter error, and allowing a sensitivity and precision comparable with those of the Wheatstone-Bridge Method (X3.5).

X3.7 *Direct-Reading Instruments*—There are available, and in general use, instruments that indicate resistance directly, by a determination of the ratio of voltage and current in bridge methods or related modes. Some units incorporate various advanced features and refinements such as digital readout. Most direct reading instruments are self-contained, portable, and comprise a stable d-c power supply with multi-test voltage capability, a null detector or an indicator, and all relevant auxiliaries. Measurement accuracies vary somewhat with type of equipment and range of resistances covered; for the more elaborate instruments accuracies are comparable to those obtained with the voltmeter-ammeter method using a galvanometer (X3.1). The direct-reading instruments do not necessarily supplant any of the other typical measurement methods described in this Appendix, but do offer simplicity and convenience for both routine and investigative resistance measurements.

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